Generation of an Aerothermal Data Base for the X33 Spacecraft

By Cathy Roberts, Sterling Software Inc.
and Loc Huynh, Eloret Institute

Abstract

The X-33 experimental program is a cooperative program between industry and NASA, managed by Lockheed-Martin Skunk Works to develop an experimental vehicle to demonstrate new technologies for a single-stage-to-orbit, fully reusable launch vehicle (RLV). One of the new technologies to be demonstrated is an advanced Thermal Protection System (TPS) being designed by BF Goodrich (formerly Rohr, Inc.) with support from NASA. The calculation of an aerothermal database is crucial to identifying the critical design environment data for the TPS. The NASA Ames X-33 team has generated such a database using Computational Fluid Dynamics (CFD) analyses, engineering analysis methods and various programs to compare and interpolate the results from the CFD and the engineering analyses. This database, along with a program used to query the database, is used extensively by several X-33 team members to help them in designing the X-33. This paper will describe the methods used to generate this database, the program used to query the database, and will show some of the aerothermal analysis results for the X-33 aircraft.

Introduction

The X-33 vehicle program is a cooperative program between industry and NASA being managed by the Lockheed-Martin Skunk Works. The goal of the program is to demonstrate new technologies in order to reduce the technical and business risks of the next generation of reusable launch vehicles (RLV). The main technologies being investigated are a new composite fuel tank design, a new integrated engine design, and a new metallic thermal protection system (TPS). The NASA Ames Research Center X-33 team is involved in the design of the TPS with BF Goodrich (formely Rohr, Inc.) being the TPS subsystem lead.

Aerodynamic Analysis Methods

The Ames X-33 team has produced an aerothermal database to aid in identifying and designing for the critical aerothermal data points on the surface of the vehicle during the X-33 missions. The database was developed using computational fluid dynamic (CFD) analysis results from the General Aerodynamic Simulation Program (GASP). GASP performs a complete (full body) 3-D, real gas, Navier-Stokes flow field solution. The gaps in the database not covered by GASP solutions were filled in using results from the Hypersonic Aerospace Vehicle Optimization Code (HAVOC)[1]. HAVOC is an hypersonic aircraft synthesis code that uses engineering analysis methods to calculate aerothermal data such as the surface temperature and wall pressure. Each method has advantages and disadvantages. The CFD program, GASP, does a more accurate analysis than the HAVOC program. However the GASP analysis takes a long time to perform and it is expensive in terms of the super computer time needed to perform each analysis. The initial analysis performed by GASP at one altitude, one mach number, and one angle of attack in the mission took roughly 50 CPU hours of super computing time on a CRAYC-90. The remaining analyses took five to ten hours of super computing time (after the initial analysis the CFD team had a better starting solution for the GASP algorithms). In the given time frame of the X-33 program this meant that the CFD team could perform about 41 analyses (19 turbulent cases and 22 laminar cases). Ideally 400 analyses (4 altitudes, 5 angle of attacks, 20 mach numbers) would be needed for the desired database. 41 analyses were not enough data to produce the desired database. HAVOC was used to fill in the gaps in the database.

A typical HAVOC run takes 10 minutes to run on an Silicon Graphics Inc. Indigo2 workstation. HAVOC performs analyses for a set of mach numbers, dynamic pressures (calculated based on altitude), and angles of attack. It can handle up to 4 dynamic pressures, 5 angles of attack, and 20 mach numbers for a single run. The draw back with HAVOC is that the analyses used are not as high fidelity as the computational fluid dynamics analysis. HAVOC uses engineering analysis methods such as tangent wedge and tangent cone coupled with reference enthalpy methods to perform the aerothermal analysis. HAVOC is an ideal tool for generating the data in the gaps left by the CFD analysis. It works quickly and the results can be used in combination with CFD to produce a complete data set.

Data Base Geometry Model

An important part of developing the X-33 aerothermal database was setting up the X-33 geometries for the two analysis programs. The outer mole line geometry was obtained from the X-33 airframe design team. The Ames CFD team set up a geometry grid for use in their program (GASP). The challenges for them involve setting up the grid such that crucial areas such as the leading edge of the fin or the nose cap of the body were modeled correctly. Their grids came out to be quite dense with data points. The geometry used by the database generation program is a coarser set of CFD data extracted from the fine grid by the CFD team. Figure 1 illustrates the database geometry model. Setting up the geometry for the HAVOC program was accomplished by editing the CFD data points to a format usable by HAVOC.

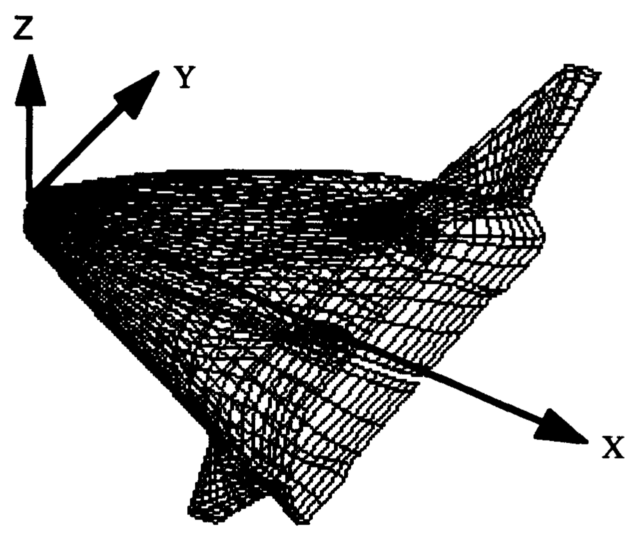

Figure 1: X33 Database Geometry

HAVOC Geometry Model

HAVOC requires that the fins, tails, and body of the vehicle be separately modeled. A graphics program called CROSS was used to inspect the CFD data and determine which range of points fall on the tail, the fin, or the body of the vehicle. CROSS displays points in a given cross section and labels them with the index number of the array which contains the points. The body, tail, and fin points were then extracted from the point arrays for each particular component of the vehicle using the index ranges determined from CROSS.

Performing the point extraction for the body results in there not being an equal number of points at each cross section due to the removal of the tail and fin points. HAVOC requires equal number of points per cross section to work correctly. The method used to generate a set of cross sections with equal number of points per cross section was to generate points at equal arc lengths around the perimeter. Linear interpolation was used to calculate the data point when the arc length fell between two known points. This method of generating data points resulted in the same number of points per cross section and points that were spaced properly for the creation of the uniform quads or panels used by HAVOC. This was the final model used for the HAVOC body analysis.

In HAVOC, the tails and fins were input as base wing components that were then translated and rotated to the proper position. The base input geometry of a HAVOC wing component is described by a series of XZ cross section points such that the X direction corresponds to the chord of the wing, the Z direction corresponds to the thickness of the wing, and the Y direction corresponds to the span direction of the wing. The leading edge root of the wing component must be positioned at (0,0,0). The base wing component can also be modeled as a wing with a biconvex cross section and a user entered aspect ratio, leading edge sweep, and taper ratio. Early versions of the X-33 geometry used the biconvex cross section wing model, while later versions of the geometry made use of the relatively new ability to enter wing data in HAVOC by a series of wing XZ cross section points. Once this data has been determined the user then must specify to HAVOC how the wing component is to be transformed (translated and rotated). The CFD extracted fin and tail point data was used to build the required HAVOC wing components.

The first step in modeling the fin or tail geometry from the extracted CFD points was to determine how to transform the given points so that the wing points were oriented as required for a HAVOC base wing component. The fin and tail CFD points were first translated so that the leading edge root point falls on (0,0,0). The program CROSS is used to determine the location of this point in the CFD data. The rotation transformations were determined by picking three points on the fin or tail: a point on the leading edge near the tip, a point on the leading edge near the root, and a point on the trailing edge near the root. These three points were used to determine the equation of the plane that lies in the planform view of the fin or tail. If this plane is transformed such that it lies in the XY plane (its normal lines up with the Z axis), the fin or tail will be in the proper orientation for HAVOC. For the X-33 fin, a rotation about the X axis of -16.7 degrees followed by a rotation about the Y axis of 10 degrees moved the plane to the proper orientation. For the vertical tail, a rotation of -90 degrees about the X axis resulted in the proper orientation. At this point the fin and vertical tail points were transformed to the correct orientation for use by HAVOC. However, the cross section points were given as YZ points for each X station while HAVOC required the cross section points to be given as XZ points at Y stations, or span stations. To generate the proper cross points a program called TRF_AND_CUT (TRansForm AND CUT) was used.

TRF_AND_CUT transforms a set of (x,y,z) points and then cuts the set with an XZ cutting plane for a series of user entered Y coordinates. It then generates a set of XZ cross section points for each Y coordinate. The program allows the user to enter the desired number of points per cross section and it was specialized for the X-33 program by adding code to generate more points in the leading edge section of the wing. This program was used to transform and generate the XZ cross sections from the X-33 fin and tail CFD data. The data points generated by TRF_AND_CUT are the sets of points used as the fin and tail base wing geometry for HAVOC. The transforms used to orient the CFD data for making XZ cuts are reversed and used as the translation and rotations for the tail and fin wing components in HAVOC. Figure 2 shows a comparison of the X-33 CFD fin and tail to the X-33 HAVOC geometry fin and tail.

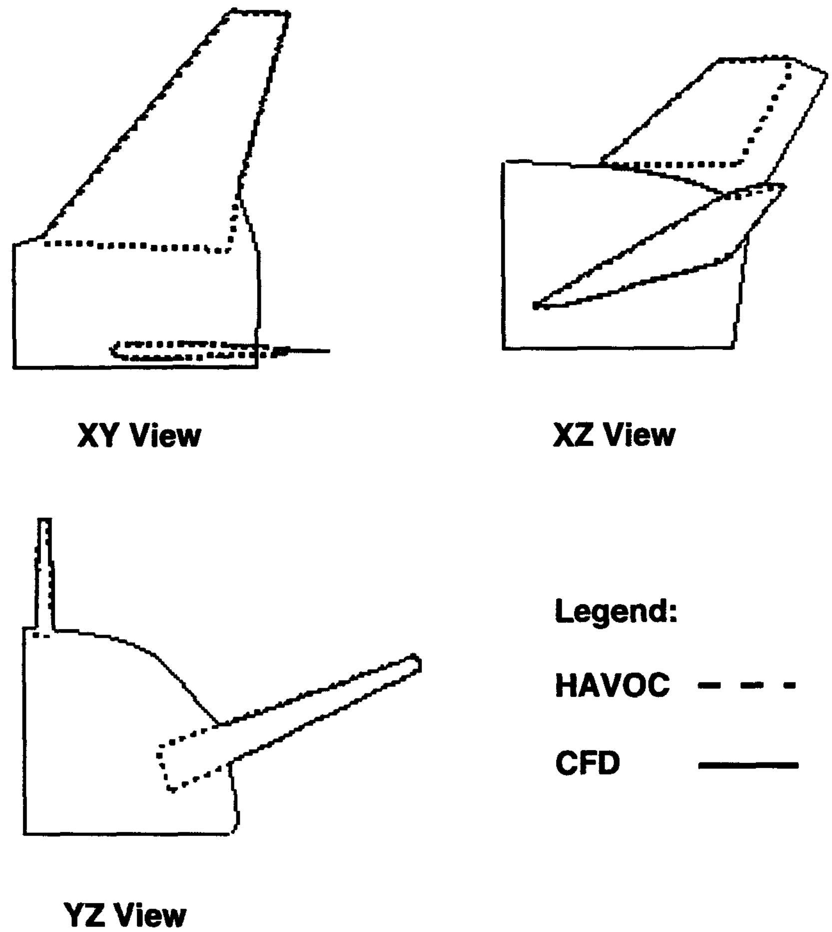

Figure 2: CFD and HAVOC Fin and Tail Comparison

Generating the Aerothermal Data Base

The aerothermal database consists of the geometry as described and the following aerothermal data at each geometry point and time in the trajectory: the wall temperature (T_w), the wall pressure (P_w), the recovery enthalpy (i_r), the film coefficient (h_c), and the convective heat transfer rate (q_c). The trajectory is described by a series of altitudes, Mach numbers, M, and angle of attacks, α, at each time step along the mission. The databases for each trajectory were stored in a single text file that averaged about 80 megabytes in size. Databases were generated for several different proposed X-33 trajectories. The database was generated by a program which uses the results from both HAVOC and GASP analyses.

Table 1: GASP and HAVOC data ranges

CFD Database	HAVOC Database
$4.0 < M < 15$	$0.1 < M < 16$
$0° < \alpha < 45°$	$0° < \alpha < 45°$
q_{cfd}	$25 < q < 600$

The database generation program started by reading in all the HAVOC and GASP analysis results. Table 1 shows the ranges of data in the GASP and HAVOC analyses data sets. Note that for the GASP analyses for each Mach number, M, and angle of attack, α, there was data for only one dynamic pressure. This is an example of the gap in the GASP data. After reading in the analysis data, the program generated a set of mach numbers, angle of attacks, and dynamic pressures (q_{bar}) based on the given trajectory at which it will calculate the aerothermal data for that mission. The aerothermal data was described as a vector: $x = [T_w, q_c, i_r, h_c, P_w]$. At a given M and α, a polynomial interpolation was performed on the GASP data to find the aerothermal data, x_{cfd}. At the same M and α and two values of dynamic pressure, q_{bar} and q_{cfd} a polynomial interpolation was performed on the HAVOC data to calculate the aerothermal data, $x_{@qbar}$, and $x_{@qcfd}$. The final aerothermal data was calculated from the results of the HAVOC and GASP data interpolations as

$$x = x_{cfd} \times \left(x_{@\,qbar} / x_{@\,qcfd}\right)_{HAVOC}.$$

This calculation was performed for every M, α, and q_{bar} along the trajectory to create the desired aerothermal database. The database generation program also contained criteria for determining whether to query the turbulent or laminar CFD and HAVOC databases based on the flight condition.

Accessing the Aerothermal Database

Once the aerothermal database was generated a tool was needed to allow users to access the database at desired points of interest on the vehicle surface. Program INTERPOLATE is this tool. INTERPOLATE reads in the aerothermal database and allows the user to enter a (x,y,z) data point and obtain the aerothermal data for that particular point at all times of the mission. It also allows the user to enter a time in the mission and obtain the aerothermal parameters for all the (x,y,z) data points in the aerothermal database. If the user requests data for a particular time the code looks up the closest two times in the database and does a simple linear interpolation to find the data at the desired time. The case where the user requests data at a particular point is more complicated because the point entered may not fall exactly on the aircraft surface.

The program has to locate the closest point on the surface of the vehicle to the entered point. This is accomplished by calculating the minimum distance of the entered point to the line segments made up by the (x,y,z) data points in each cross section. The minimum distance of a point to a line segment is calculated by creating a triangle from the line segment end points to the entered point. The lengths of the sides of the triangle are then calculated. The resulting triangle will appear as one of three cases illustrated in Figure 3. The minimum distance is illustrated for each case. The case used to calculate the distance is determined based on the angles between line P1 and line 12 and between line P2 and line 12. If the two angles are both less than 90.0 degrees, case II results. If the angle between P1 and 12 is greater than 90 degrees, case III results and if the angle between P2 and line 12 is greater than 90 degrees, case I results. The minimum distances from the point to each line segment are saved for later use.

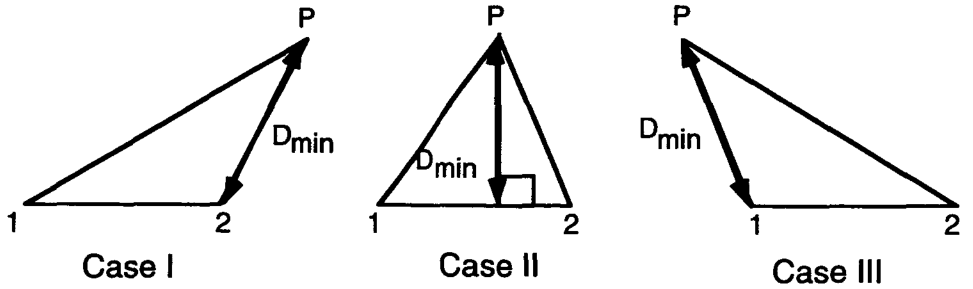

Figure 3: Illustration minimum distances from a point to segment 12

The program finds the two line segments in neighboring cross sections that are closest to the point, P, using the saved minimum distances calculated for all the cross section line segments. Figure 4 illustrates the two line segments nearest an entered point: P11 to P12 and P21 to P22. Aerothermal data is known at the end points of the two line segments. From P11 and P12, point P1 is located by dropping a line from the entered point P to the line segment such that the line is perpendicular to the line segment. Point P2 is located in the same fashion from P21 and P22. The aerothermal data is calculated for points P1 and P2 by using linear interpolation based on the distances of the line segment end points from P1 and P2 and the aerothermal values at P11, P12, P21, and P22. A similar process is then followed to find the final point and interpolate to find the aerothermal data at this point with P1 and P2 making the line segment endpoints. The program then informs the user of the location of point PF and it's distance from the entered point. Finally it performs the linear interpolations for all the angle of attacks, mach numbers, and dynamic pressures.

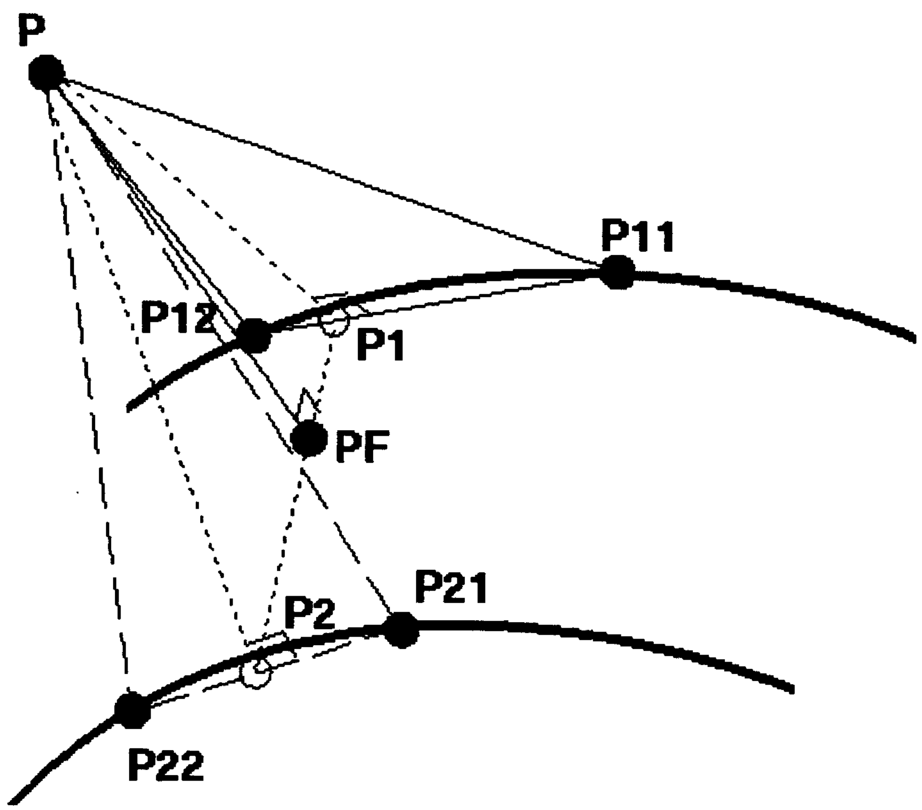

Figure 4: Illustration of interpolation program point locations

Verification of Results

To verify the X-33 database results, program INTERPOLATE was used to generate data to produce plots of the aerothermal data at arc lengths around a cross section at a longitudinal station for the peak heating case in the trajectory. The arc lengths were measured from the windward center line of the cross section in a counter clockwise direction. The database was then regenerated without the peak heating CFD GASP case. This allowed the database results to be compared to the peak heating CFD GASP case results to verify that the aerothermal database results were acceptable. Figures 5 and 6 show the surface temperature comparisons at a longitudinal station near the nose and near the tail. In either case the largest difference in temperatures was less than 100 °F. This data was within acceptable bounds for use in designing the TPS. Similar comparisons were made for other aerothermal data (such as the wall pressure) and for more X station locations. In all the cases examined the data was within required bounds.

Another method used to check the X33 database was to create a color picture of the surface geometry where magenta colors indicated hot temperatures and blue colors lower temperatures. These views of the vehicle helped to point out trouble spots to look at more carefully in the verification of the database data. One of the difficulties of verifying the data was the shear magnitude of the data. There was data for 1344 geometry points and 736 different trajectory points or almost a million data points! By examining the color coded plot of surface temperatures and other aerothermal data a quick visual check could be performed on big chunks of data.

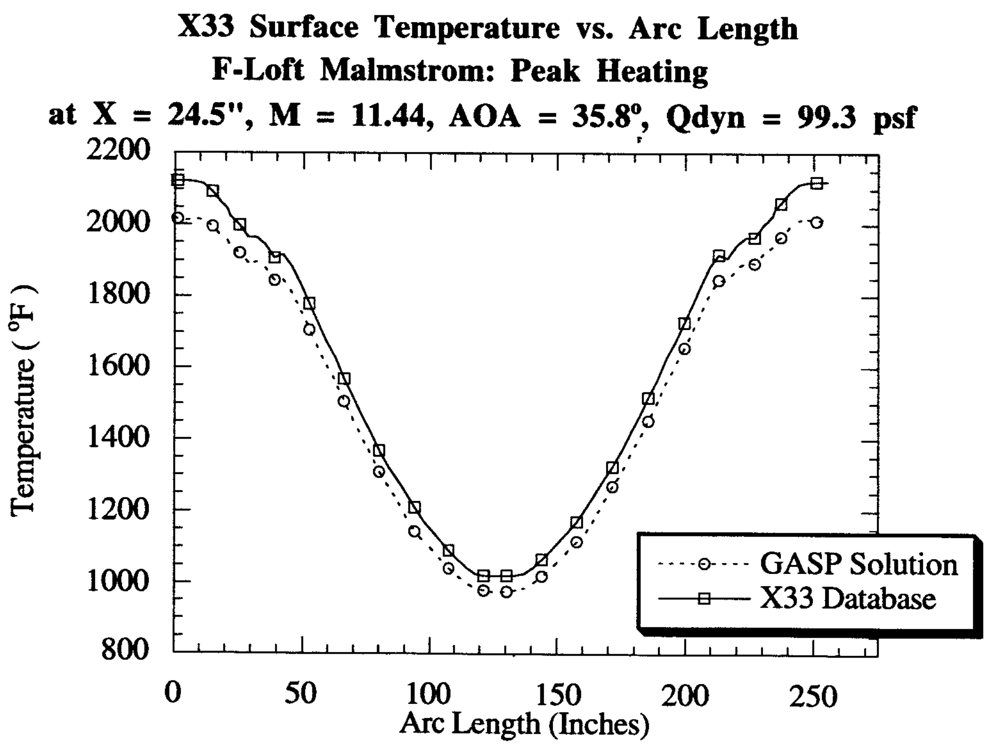

Figure 5: X-33 Surface Temperatures near the nose

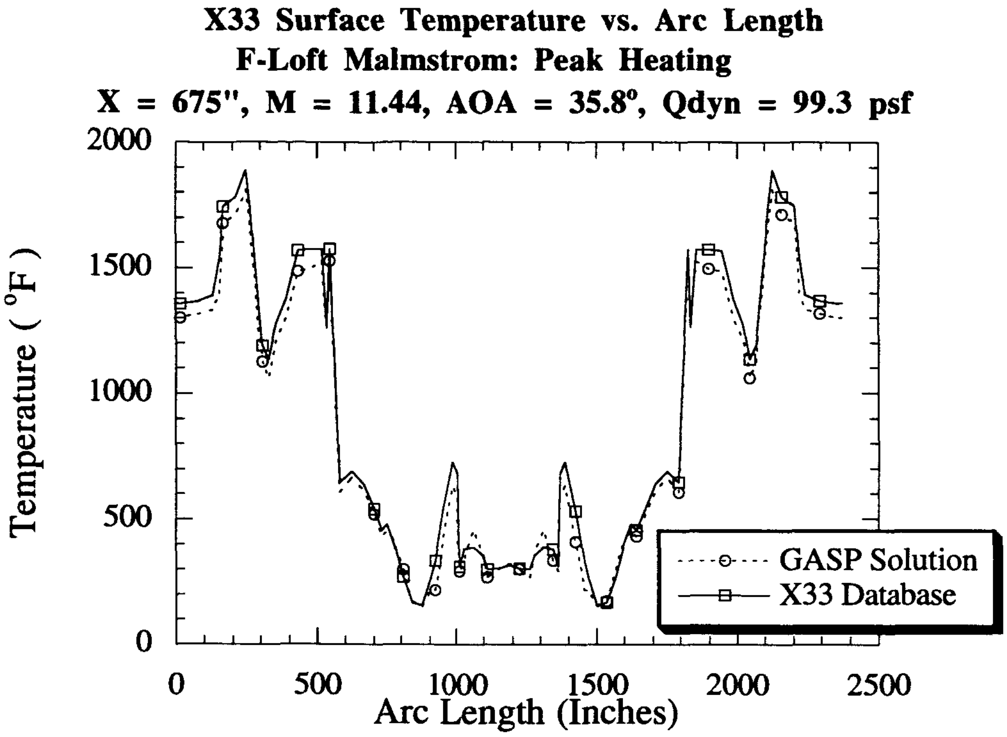

Figure 6: X-33 Surface Temperatures near the tail

Summary

In summary, GASP and HAVOC geometry models were generated and analyses were performed on the X-33 vehicle to be used in building the aerothermal database. The GASP analyses were accurate but due to the tight schedule of the X-33 program there was not enough time to run enough GASP cases to produce all the desired aerothermal data. HAVOC was used to interpolate the aerodynamic heating parameters with the free-stream dynamic pressure and to fill in the gaps in the GASP data since it produces results significantly faster. The database generation program combines the results from GASP and HAVOC by using polynomial interpolation to produce the desired aerothermal database. The database was verified by leaving out a GASP case and comparing the database results to this GASP case. It was shown that the database was accurate within the bounds needed for the X-33 program.

Once the data was verified it was distributed to the design team along with the database query program, INTERPOLATE, for use in designing the thermal protection system for the X-33. The database was used to find aerothermal data at given points on the aircraft. This data allows engineers to the pick the appropriate materials to withstand the aerothermal environment at that point, and compute required TPS insulation thickness. These databases were used extensively by BF Goodrich (formerly Rohr, Inc.) along with the database query program INTERPOLATE to help them design the TPS for the X-33 within the tight schedule of the X-33 program.

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Cathy Roberts' Curriculum Vitae

Cathy Roberts has been working for Sterling Software Inc. since September of 1987 as a software specialist on the NASA Ames Research Center support services contract at Moffett Field, California. She supports software used to model geometry for the Hypersonic Aerospace Vehicle Optimization Code in the NASA Ames system analysis branch and is also the UNIX systems administrator for eighteen Silicon Graphics Inc. work stations and two Sun workstations in the branch. Ms. Roberts graduated from Purdue University in 1984 with a bachelor of science in mechanical engineering and graduated from Cornell University in 1987 with a master of science in mechanical engineering. She is a member of the Society of Women Engineers and currently serves on the Electronic Communications Committee as the National Gatekeeper and the Webmeister.

Loc Huynh's Curriculum Vitae

Loc Huynh currently works for Eloret Institute and has worked as a contractor at NASA Ames Research Center for over 10 years. Mr. Huynh has incorporated Computational Fluid Dynamics (CFD) calculations to build an aerothermal database for the X-33 vehicle, contributed to the integrated Aircraft Synthesis Program (ACSYNT) and NASA Engine Performance Program (NEPP), developed an engineering method and wrote the "Nose-to-Tail" program to predict the performance of SCRAMJET/RAMJET propulsion for supersonic/hypersonic vehicles and built a generic turboprop model for CTAS (Center TRACON Automation System). Mr. Huyhn has authored or co-authored over 10 journal articles, conference papers, and technical reports. He graduated from San Jose State University in 1985 with a bachelor of science in Mathematics with an emphasis in computer science.